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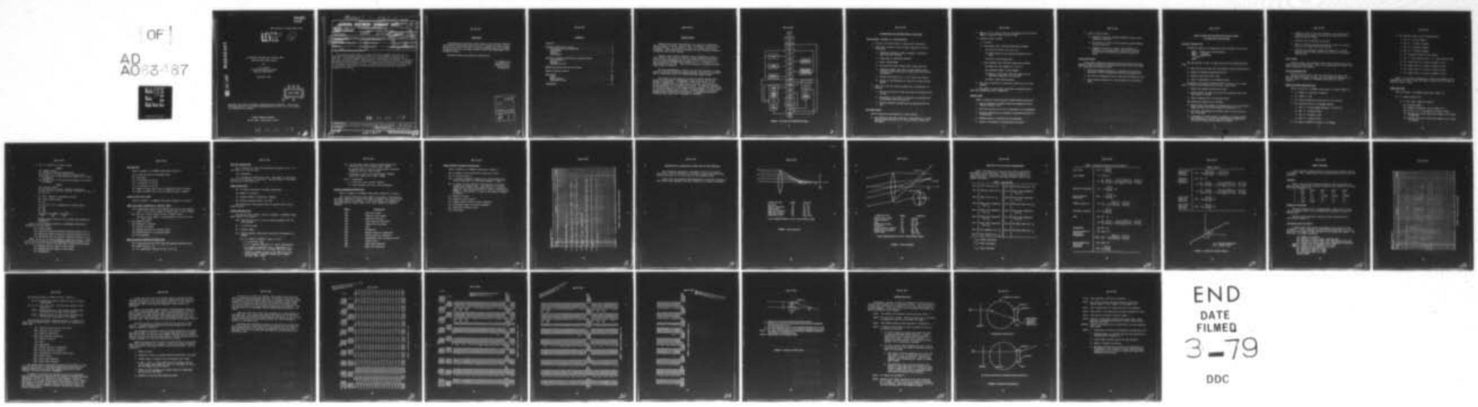

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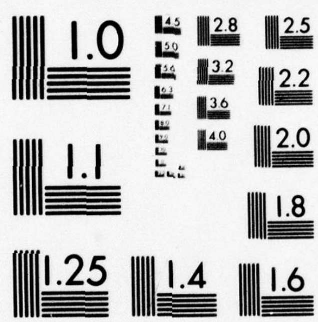

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NATIONAL BUREAU OF STANDARDS-1963-A

NWC Technical Memorandum 2626

A COMPUTER PROGRAM FOR OPTICAL RAY TRACING AND LENS DESIGN

by

G.K. Hearn
Electro-Optics Division
Weapons Department

February 1976

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China Lake, California 93555

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Jun–Jul 75

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The purpose of this report is to help the optical designer with little or no knowledge of programming to make efficient use of this powerful designing tool. To this end, a flow chart ~~(Figure 1)~~, an outline of capabilities and options open to the user, and instructions for implementation of the options are included. In addition, definitions of the aberrations used in the program and a discussion of various methods of calculation appear within the text. A sample problem is run and the program output is interpreted, and finally a troubleshooting section explaining some common error statements is included.

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FOREWORD

This preliminary report was written to provide a reference to anyone interested in utilizing the optical design and analysis computer program written by W. C. Fitzgerald. The writing of this report was done in June and July of 1975 and it was reviewed for technical accuracy by W. C. Fitzgerald. This program has been used in the design and analysis of several systems including AIM-9L, AGILE, and APD seeker systems.

This report is released at the working level for information only.

P. G. ARNOLD, Head
Electro-Optics Division
Weapons Department
25 February 1976

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CONTENTS

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INTRODUCTION

Manually performing exact numerical ray traces for complicated optical systems is always a tedious task. Accordingly, simplifications and approximations can be applied to arrive at paraxial ray-tracing techniques. These techniques are quicker, but are frequently inadequate to describe real optical systems.

However, modern digital computers can be programmed to conduct exact numerical ray traces and even to optimize system parameters when a fairly close approximation to the ideal system is read in as data. Such a program is 342*WCRF.OPTIC, designed by W. C. Fitzgerald of the Naval Weapons Center (NWC). This report describes the program and gives instructions for using it.

The user knowledgeable in optics can apply this program to a large variety of optical and infrared design problems, including the determination of static gain curves for reticle-modulated seeker systems.

The purpose of this report is to help the optical designer with little or no knowledge of programming to make efficient use of this powerful designing tool. To this end, a flow chart (Figure 1), an outline of capabilities and options open to the user, and instructions for implementation of the options are included. In addition, definitions of the aberrations used in the program and a discussion of various methods of calculation appear within the text. A sample problem is run and the program output is interpreted, and finally a troubleshooting section explaining some common error statements is included.

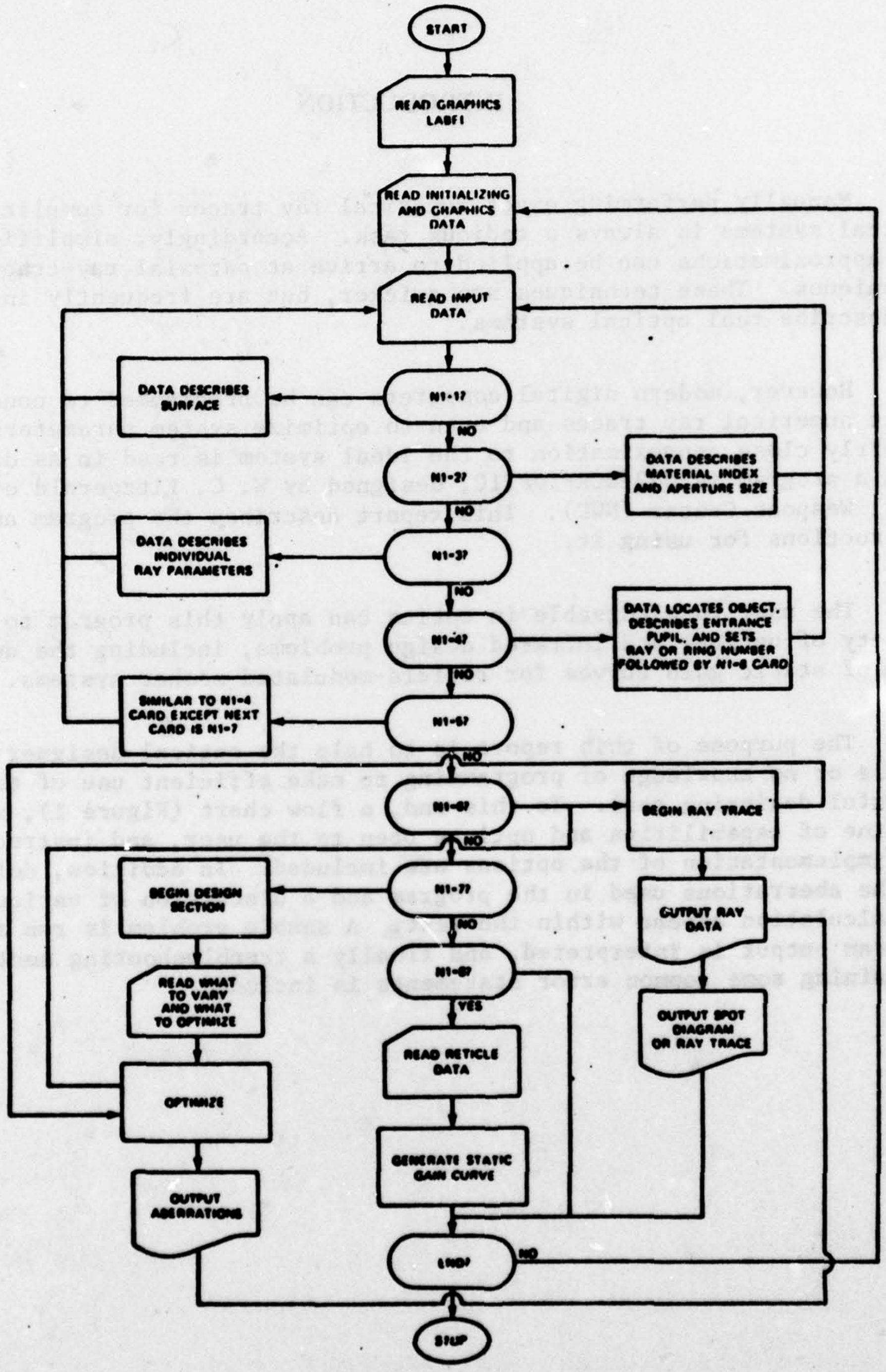

FIGURE 1. Flow Chart for 342*WCRF.OPTIC Program.

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CAPABILITIES AND OPTIONS OPEN TO THE USER

PROGRAMMING OPTIONS OF 342*WCRF.OPTIC

1. The user can choose batch or demand mode of operation.
2. Input data is used to select various computation options, as follows:
   a. Spherical, aspheric, aconic, parabolic, hyperbolic, and elliptical surfaces
   b. Refracting or reflecting surfaces
   c. Tilts, decenterings
   d. Ray-trace only mode, design mode, static gain mode
   e. Graphics options: Ray trace or spot diagram (other versions of WCRF.OPTIC may be required for CRT display of graphics)
   f. Whether ray traces for 1, 2, or 3 colors are desired
   g. Numbers of and parameters of rays to be traced through system.
3. Input data can also control program flow of operations, as follows:
   a. Several operations on input data may be performed within one run.
   b. Operations on the results of previous calculations may be performed within the same run.
   c. Several different problems may be computed within one run.

RAY-TRACE MODE

Used to demonstrate performance of a given system.

1. Any numbers of rays (up to 400 for 1 color, 900 for 3 colors) with any specifications may be traced through as many as 30 interfaces.

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2. Fans of rays or rings of rays can be generated (user specifies number of rings or number of rays in fan).

3. Graphics options include:

   a. No plots

   b. Ray tracing (user specifies graph axis extremes)

      (1) Plane for traces, X-Y, X-Z, Y-Z

      (2) Which surface of the system the diagram starts with

      (3) New or old plotting frame

   c. Spot diagrams (user specifies graph axis extremes)

      (1) Plane for spot diagram X-Y, X-Z, Y-Z

      (2) Interface number of spot diagram

      (3) Option to find image plane and image size and make spot diagram at this location

      (4) New or older plotting frame.

4. Data can be written for a specified surface on to the last surface.

5. The number of rays within a specified incremental radius about the focused spot may be requested.

DESIGN MODE

(Used to optimize a given system by varying system parameters).

1. User may specify N variables which the program may adjust (radii, position, etc.)

2. User then selects up to N of 13 aberrations to be minimized.

3. Relative weighting may be applied to aberrations desired to be corrected.

4. Maximum number of iterations may be specified.

5. Limits on increments are determined by the user.

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6. Output results include:

   a. Aberration terms and variable parameter values corresponding to iteration

   b. Ray data for 17 rays traced through the system defined by last interation

   c. Graphical ray trace of system (spot diagrams not possible in the design mode). Options are the same as ray-trace mode graphics options for ray-tracing plots.

STATIC-GAIN MODE

In this mode information generated by the calculation of a spot diagram is used to predict the modulation efficiency versus field angle for a rotating mirror/reticle system.

1. Since spot diagram information is required, the ray-trace mode must be used in conjunction with the static-gain mode.

2. Any reticle configuration can be read into the system as data.

3. Any frequency response curve can be read into the system as data.

INSTRUCTIONS FOR IMPLEMENTING SPECIFIC MODES OF OPERATION AND OPTIONS

GENERAL INFORMATION

Calling the program is accomplished by the following instructions:

```
@RUN     (Proper user identification)
@ASG,A     342*WCRF.
@XQT     342*WCF.OPTIC
....DATA....
@FIN
```

The data whether on file or cards will be of the following general form:

1. User name and job name card (for graphics output identification)
2. System and graphics specification card
3. Surface data and ray data cards
4. Type of computation to be conducted cards.

To continue with another problem within the same run it is necessary to include the following after the type 4 cards above:

1. System and graphics specification cards
2. Surface and/or ray data cards (only for parameters which the user wishes to change)
3. Type of computation to be conducted cards.

The conventions adopted are as follows:

1. Mirrors shall have indexes of refraction of -1.0 at all colors; Mangin mirrors shall have indexes of refraction of -n.
2. The X-axis corresponds to the optic axis, Y is up, and Z is out of the page.
3. A parabolic or aconic surface is denoted by a normal surface card followed by a surface card containing the negative of the surface number and the aspheric constants.

4. Instead of using on axis lens thickness, this information is contained in the input in the form of the location of the surface along the X-axis.

5. Distances may be expressed in any unit.

6. Radii of curvature are positive when the center of curvature occurs on the right side of the surface.

7. Elliptic and hyperbolic surfaces are denoted by a surface card with surface number greater than 100 plus the necessary defining data.

DATA CARDS

Lists of items to be included on data cards for formats and option specification are given below. Refer to the coding sheet in Figure 2 for column information and examples.

Plotting Identification Card

Plotting identification card must include NWC code number and user name and can include job name. Up to 36 alphameric characters can be used. Refer to Example 1 on FORTRAN coding sheet for format (Figure 2).

System and Graphics Specification Card

Refer to Example 2 on FORTRAN coding sheet for format (Figure 2).

1. IT = Number of interfaces (surfaces)

2. JT = Number of rays

3. IW = First interface for which data is to be written

4. NR = Specifies type of ray diagram desired

   a. NR = 1: No ray diagram (NR must = 1 if NS ≠ 1)

   b. NR = 2: X versus Y plot

   c. NR = 3: X versus Z plot

   d. NR = 4: Y versus Z plot

5. IR = First interface to appear on ray diagram

6. NS = Specifies type of spot diagram desired

   a. NS = 1: No spot diagram

   b. NS = 2: X versus Y diagram

   c. NS = 3: X versus Z diagram

   d. NS = 4: Y versus Z diagram

   e. IS = Interface number of spot diagram

   f. NF = 1 → New plotting frame; = 2 → same plotting frame

   g. XL = Lower limit of x values to appear on plot

   h. XU = Upper limit of x values to appear on plot

   i. YL = Lower limit of y values to appear on plot

   j. YU = Upper limit of y values to appear on plot

NOTE: If Y-Z plane is requested for either ray diagrams or spot diagrams, XL, XU refer to lower and upper y values and YL, YU refer to lower and upper z values.

Surface Data Cards

Refer to Example 3 on FORTRAN coding sheet (Figure 2).

N1 = 1 → Read interface data

a. 0 < N2 < 100 → spherical surface

   N2 = Surface number

   A1 = Radius of curvature, for $R \geq 6000$, $R = \infty$

   A2, A3, A4 = X, Y, Z coordinates of surface vertex

   A5 = Surface tilt of the vertex with respect to X-Y plane (in degrees)

   A6 = Surface tilt of the vertex with respect to X-Z plane (in degrees)

b. $N2 < 0 \rightarrow$ parabolic or aconic surface

Card 1

N2 = Surface number
A1 = Radius of curvature (meaningless)
A2, A3, A4 = X, Y, Z coordinates of surface vertex
A5 = Surface tilt of the vertex with respect in X-Y plane (in degrees)
A6 = Surface tilt of the vertex with respect to X-Z plane (in degrees)

Card 2

-N2 = Surface number
A1, A2, A3, A4, A5, and A6 = Aspheric coefficients

$$x = A1 \cdot y^2 + A2 \cdot z^2 + A3 \cdot r^4 + A4 \cdot r^6 + A5 \cdot r^8 + A6 \cdot r^{10}$$
$$r^2 = y^2 + z^2$$

c. $N2 > 100 \rightarrow$ elliptic or hyperbolic surface

N2 - 100 = Surface number

$A1 = R_A$

A2, A3, A4 = X, Y, Z coordinates of surface vertex

$A5 = R_B^2$

$A6 = R_G^2$

$$\frac{(x - A1)^2}{R_A^2} + \frac{(y - A2)^2}{R_B^2} + \frac{(z - A3)^2}{R_G^2} = 1$$

R_B^2 and/or R_G^2 are positive for an ellipse and negative for a hyperbola.

. $N1 = 2 \rightarrow$ Read refractive indexes at 3 wavelengths and aperture information for each surface

N2 = Surface number

A1 = Refractive index for material *following* surface N2 at λ_1

A2 = Refractive index for material *following* surface N2 at λ_2

A3 = Refractive index for material *following* surface N2 at λ_3

NOTE: If A1, A2, A3 are all negative, surface is a mirror. If N2 = 1, A1 > 0, A2 = 0, and A3 = 0, only one-color rays will be traced. If N2 = 1, A1 > 0, A2 > 0, and A3 = 0, only first 2 colors will be traced.

A4 = Maximum aperture radius at this surface

A5 = Minimum aperture radius at this surface

A6 = Meaningless.

Ray Data Cards

Refer to Example 3 on FORTRAN coding sheet (Figure 2).

N1 = 3 Read ray data for individual rays

N2 = Ray number

A1 = X coordinate of ray N2

A2 = Y coordinate of ray N2

A3 = Z coordinate of ray N2

A4 = Angle ray makes with X axis in tangential plane in degrees

A5 = Angle ray makes with X axis in sagittal plane in degrees

COMPUTATION-TYPE CARDS

Refer to Example 3 on FORTRAN coding sheet (Figure 2) for format.

Object and Aperture Information for Ray-Trace Mode

N1 = 4 Read object position and generate ray data for spot diagram

N2 =
- If 0 < N2 < 20 N2 = number of rings of rays for spot diagram
- If N2 > 20 N2 = number of rays in square lattice
- If N2 < 0 N2 = number of rays generated in one half of the fan of rays

A1 = Range of object

A2 = Elevation in degrees

A3 = Azimuth in degrees

A4 = Maximum aperture (at entrance pupil)

A5 = Minimum aperture (at entrance pupil)

A6 = Stop position

Object and Aperture Information for Design Mode

N1 = 5 Read aperture and field angle and generate aberration rays

N2 = Number of rays = 17

A1 - A6 - Identical to values for N1 = 4 A1 - A6

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Ray Trace Command Card

N1 = 6 Compute ray trace from information contained on N1 = 1, 2, and either 3 or 4 but not both.

N2 = Meaningless

A1 = Increment of radius about focus. The number of rays within this circle is contained in the output. Then the radius is incremented and rays are counted again, etc.

Design Command Card

N1 = 7 Compute aberrations--automatic design mode

N2 = Number of variables

A1 → Defines number of iterations = 1000/A1

A2 → Defines increment limit ≈ A2 * DVS

The following two descriptions refer to special cards for the design section.

Variable Specification Card

One card for each variable. Refer to Example 4 on FORTRAN coding sheet (Figure 2) for format.

DVS → Used with A2 on N1 = 7 card to define increment limit for each variable

WV → 1.0 for all cases

KS = Surface number

LS = Type of variable (what about the surface the computer can change)

LS = 1 → radius of curvature ΔC_{KS} $(C = 1/r)$

= 2 → X position ΔX_{KS}

= 3, 4, 5 aspheric constants A, B, and C, respectively

= 6, 7 aspheric constants E and F, respectively (A-F correspond to 2nd, 4th....through 10th order terms)

= 8 allows a change in radius at the same rate as the vertex changes → thickness changes, power remains the same; $\Delta r_{KS} = -\Delta X_{KS}$

LS = 9 no thickness change distance between present and following surface is unchanged; $\Delta X_{KS} = \Delta X_{KS+1}$

= 10 changes shape of lens but retains power, curvatures change at same rate; $\Delta C_{KS} = \Delta C_{KS+1}$

= 11 surfaces 1 and 3 of a second surfaced (Mangin) mirror must remain equal; $\Delta C_{KS} = \Delta C_{KS+2}$

MS = 1 → Meaningless

= 2 → enter ray trace--continue reading

= 3 → end of design input data, start optimizing

Aberration Optimization Selection Card

Refer to Example 5 on FORTRAN coding sheet (Figure 2) for format.

FZP = Desired effective focal length of the system. The following variables correspond to factors that can be optimized. One card specifies the action taken on all factors. A factor set equal to 1.0 implies no correction desired, higher values (i.e., 10.0) require the program to optimize.

Factor	Corrects for
WBF	Back focal length
WFZ	Effective focal length
WSA	Spherical aberration
WSZ	Zonal spherical aberration
WPC	Primary field curvature
WCM	Coma
WAT	Astigmatism
WST	Oblique spherical (tangential)
WSS	Oblique spherical (sagittal)
WCL	Longitudinal color (transverse axial)
WCT	Lateral color
WZL	Lower zonal spherical
WZU	Upper zonal spherical

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Reticle Modulation Calculation Command Card

Refer to Example 3 on FORTRAN coding sheet (Figure 2).

N1 = 8 Compute reticle modulation--static-gain curves

N2 = 0 → No data read in

N2 = 1 → Read in frequency response curve (data should be in format illustrated in coding sheet Example 7, Figure 2)

N2 = 2 → Read in reticle pattern (transmission in each zone, (TAU(K)) and response curve. Data should be in formats illustrated in coding sheet Examples 6 and 7, respectively, Figure 2. That is, the first N2 = 2 card has the format of Example 6. The next N2 = 2 card has the format of Example 7 in Figure 2.

A1 = Radius of reticle

A2 = Length of reticle sector

A3 = Angular width of reticle sector (degrees)

A4 = Incremental angle of rotation (degrees)

A5 = Rotational frequency (cps)

A6 = Scan radius

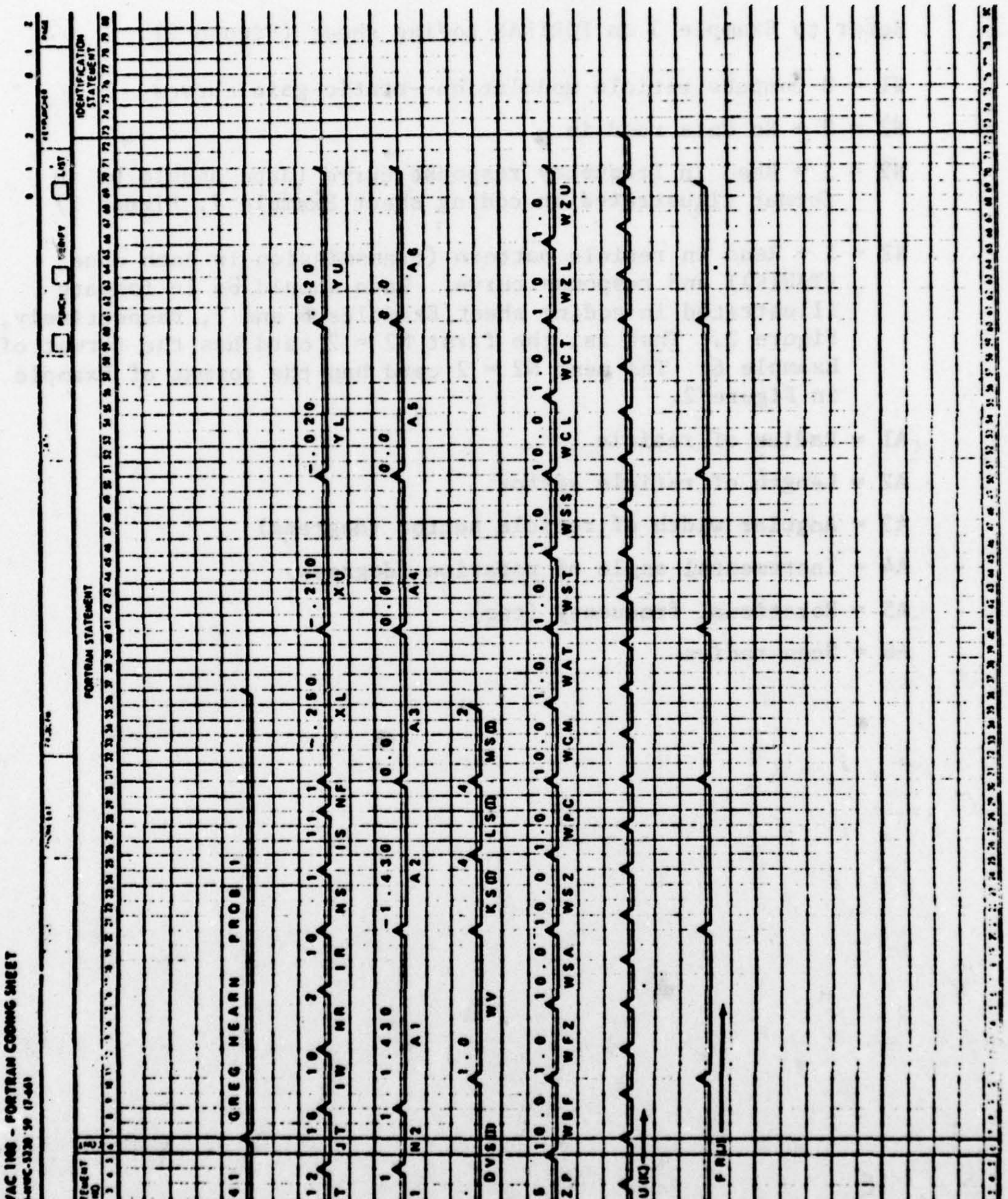

FIGURE 2. Sample of Filled-In FORTRAN Coding Sheet.

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DEFINITIONS OF ABERRATION TERMS USED IN THIS PROGRAM

Since different mathematical treatments of optical ray tracing give rise to different meanings for the same or similar aberration names, a brief definition for the terms used in this program follows.

These terms are explained using diagrams for on-axis rays (Figure 3) and off-axis rays (Figure 4), and the definitions are grouped accordingly.

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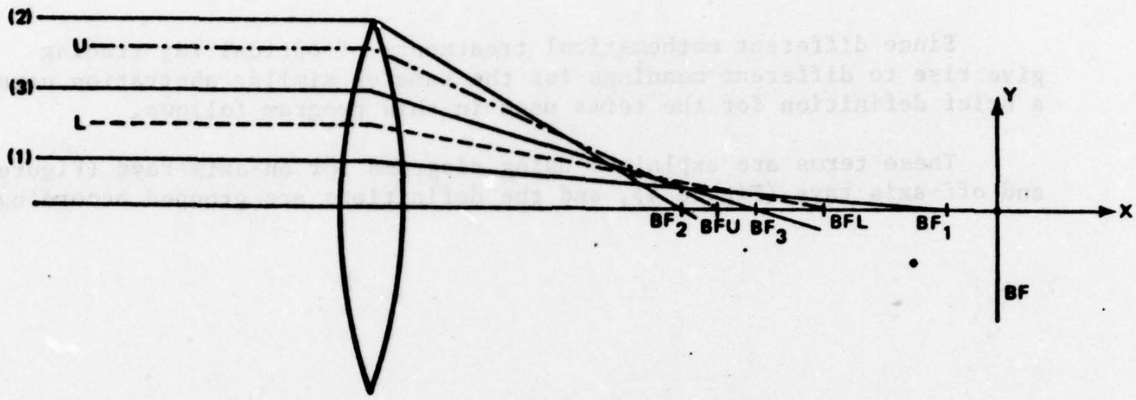

"ABERRATION" NAME	SYMBOL	DEFINITION
BACK FOCUS	BF	$BF - BF_1$
SPHERICAL ABERRATION	SA	$BF_2 - BF_1$
ZONAL SPHERICAL	ZSA	$BF_3 - BF_1$
LOWER ZONAL SPHERICAL	ZSL	$BFL - BF_1$
UPPER ZONAL SPHERICAL	ZSU	$BFU - BF_1$
LONGITUDINAL COLOR	LCH	$BF_{3C} - BF_{3F}$*

*C AND F SUBSCRIPTS REFER TO C AND F LIGHT (DIFFERENT COLORS).

FIGURE 3. On-Axis Aberrations.

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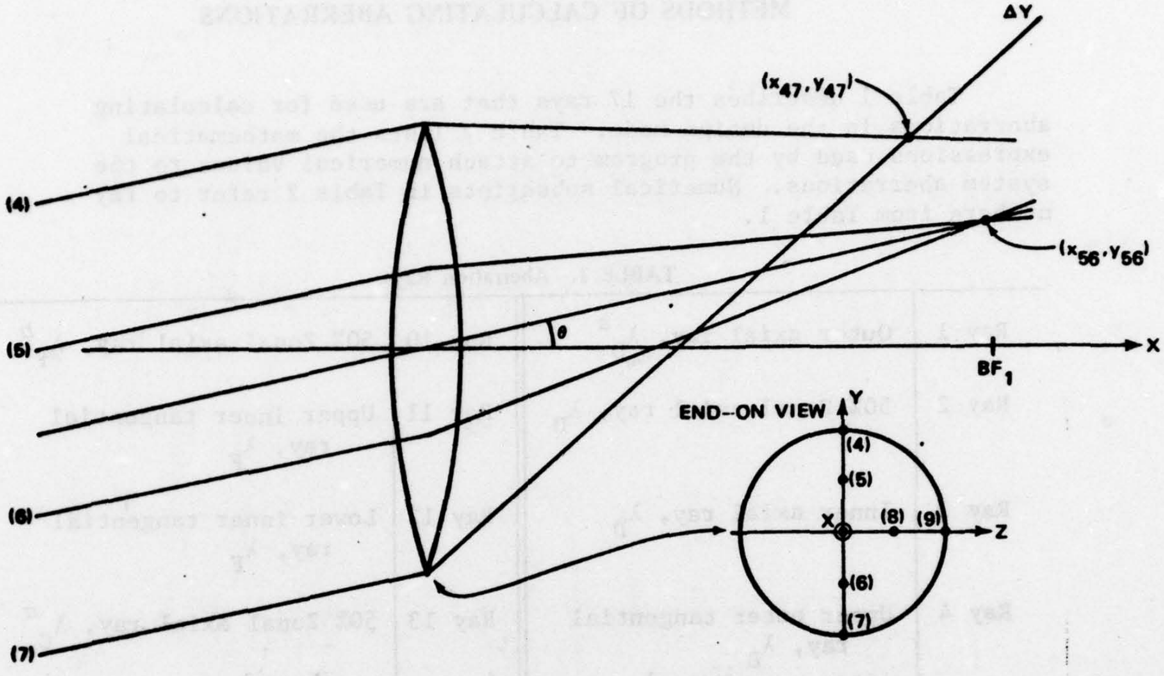

"ABERRATION" NAME	SYMBOL	DEFINITION
EFFECTIVE FOCAL LENGTH	EFL	$Y_{56}/\sin\theta$
PRIMARY CURVATURE	PC	$X_{56} - BF_1$
COMA	CM	$Y_{47} - Y_{56}$
SECONDARY CURVATURE	SC	$X_{89} - BF_1$
ASTIGMATISM	AT	PC − SC
OBLIQUE TANGENTIAL SPHERICAL	OST	$X_{47} - X_{56}$
OBLIQUE SAGITTAL SPHERICAL	OSS	$X_{89} - X_{56}$
LATERAL COLOR	TCH	$Y_{56C} - Y_{56F}$ *

* C AND F SUBSCRIPTS REFER TO C AND F LIGHT (DIFFERENT COLORS).

FIGURE 4. Off-Axis Aberrations.

METHODS OF CALCULATING ABERRATIONS

Table 1 describes the 17 rays that are used for calculating aberrations in the design mode. Table 2 lists the mathematical expressions used by the program to attach numerical values to the system aberrations. Numerical subscripts in Table 2 refer to ray numbers from Table 1.

TABLE 1. Aberration Rays.

Ray 1	Outer axial ray, λ_D[a]	Ray 10	50% Zonal axial ray, λ_F[b]
Ray 2	50% Zonal axial ray, λ_D	Ray 11	Upper inner tangential ray, λ_F
Ray 3	Inner axial ray, λ_D	Ray 12	Lower inner tangential ray, λ_F
Ray 4	Upper outer tangential ray, λ_D	Ray 13	50% Zonal axial ray, λ_C[c]
Ray 5	Upper inner tangential ray, λ_D	Ray 14	Upper inner tangential ray, λ_C
Ray 6	Lower inner tangential ray, λ_D	Ray 15	Lower inner tangential ray, λ_C
Ray 7	Lower outer tangential ray, λ_D	Ray 16	25% Zonal axial ray, λ_D
Ray 8	Outer sagittal ray, λ_D	Ray 17	75% Zonal axial ray, λ_D
Ray 9	Inner sagittal ray, λ_D		

[a] λ_D = Middle wavelength.

[b] λ_F = Short wavelength.

[c] λ_C = Long wavelength.

TABLE 2. Mathematical Expressions for Aberrations (Figure 5).

Back focus	$BF = -Y_3 \dfrac{\cos \alpha_3}{\cos \beta_3}$
Focal length	$F = YI/\sin \theta$
	$YI = \left(Y_5 \dfrac{\cos \alpha_4}{\cos \beta_5} - y_6 \dfrac{\cos \alpha_6}{\cos \beta_6}\right) \Big/ \left(\dfrac{\cos \alpha_5}{\cos \beta_5} - \dfrac{\cos \alpha_6}{\cos \beta_6}\right)$
Spherical aberration	$SA = -Y_1 \dfrac{\cos \alpha_1}{\cos \beta_1} - BF$
Zonal spherical aberration	$ZSA = -Y_2 \dfrac{\cos \alpha_2}{\cos \beta_2} - BF$
Primary curvature	$PC = \left(Y_6 - Y_5\right) \Big/ \left(\dfrac{\cos \beta_5}{\cos \alpha_5} - \dfrac{\cos \beta_6}{\cos \alpha_6}\right)$
Secondary curvature	$SC = -Z_9 \dfrac{\cos \alpha_9}{\cos \alpha_9}$
Coma	$CM = Y\theta - YI$
	$Y\theta = \left(Y_4 \dfrac{\cos \alpha_4}{\cos \beta_4} - Y_7 \dfrac{\cos \alpha_7}{\cos \beta_7}\right) \Big/ \left(\dfrac{\cos \alpha_4}{\cos \beta_4} - \dfrac{\cos \alpha_7}{\cos \beta_7}\right)$
Astigmatism	$AT = PC - SC$
Oblique spherical aberration (tangential)	$ST = PCM - PC$
	$PCM_2 = \left(Y_7 - Y_5\right) \Big/ \left(\dfrac{\cos \beta_4}{\cos \alpha_4} - \dfrac{\cos \beta_7}{\cos \alpha_7}\right)$
Oblique spherical aberration (sagittal)	$SS = SCM - SC$
	$SCM = Z_8 \dfrac{\cos \alpha_8}{\cos \alpha_8}$

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TABLE 2. (Contd.)

Longitudinal chromatic aberration	$LCh = -Y_{10}\left(\dfrac{\cos\beta_{10}}{\cos\alpha_{10}}\right) + Y_{13}\left(\dfrac{\cos\beta_{13}}{\cos\alpha_{13}}\right)$
Transverse chromatic aberration	$TCh = YF - YC$ $YF = \left(Y_{11}\dfrac{\cos\alpha_{11}}{\cos\beta_{11}} - Y_{12}\dfrac{\cos\alpha_{12}}{\cos\beta_{12}}\right)\Big/\left(\dfrac{\cos\alpha_{11}}{\cos\beta_{11}} - \dfrac{\cos\alpha_{12}}{\cos\beta_{12}}\right)$ $YC = \left(Y_{14}\dfrac{\cos\alpha_{14}}{\cos\beta_{14}} - Y_{15}\dfrac{\cos\alpha_{15}}{\cos\beta_{15}}\right)\Big/\left(\dfrac{\cos\alpha_{14}}{\cos\beta_{14}} - \dfrac{\cos\alpha_{15}}{\cos\beta_{15}}\right)$
Lower zonal spherical aberration	$ZSL = -Y_{16}\dfrac{\cos\alpha_{16}}{\cos\beta_{16}} - BF$
Upper zonal spherical aberration	$ZSU = -Y_{17}\dfrac{\cos\alpha_{17}}{\cos\beta_{17}} - BF$

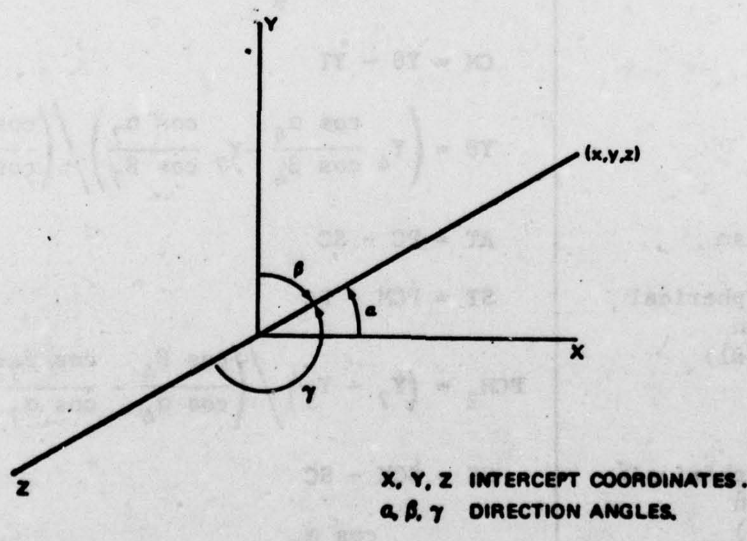

FIGURE 5. Coordinates for Aberration Definitions.

SAMPLE PROBLEM

In this section a sample problem is stated and the method of solving it is given. Then a sample output and the interpretation of the output are presented.

PROBLEM

Given a lens with the following parameters, find the optimum lens shape to reduce coma while driving the effective focal length to 3.5 inches. The initial parameters are:

I	R(I)	XV(I)	$N_D(I)$	$N_F(I)$	$N_C(I)$
1	7000	0.5	1.0	1.0	.1.0
2	-1.5	3.0	1.51124	1.5169	1.50883
3	-1.0	3.35	1.0	1.0	1.0
4	7000	6.801	1.0	1.0	1.0

METHOD OF SOLUTION

Using the design section of 342*WCRF.OPTIC, allow radii of curvature for surfaces 2 and 3 to be variables while choosing to correct for EFL and coma.

The data cards required to perform the above calculations are illustrated in Figure 6.

INTERPRETATION OF OUTPUT

A sample output data printout consisting of four sheets is shown in Figure 7. Sheet 1 displays the input data which describes the initial system plus the output for each iteration of the design mode section. The first group of columns represents

R = Radius of curvature
XV = Position of vertex along x (optical) axis
YV = Position of vertex along y axis (decentering direction)
ZV = Position of vertex along z axis (decentering z direction)
Gamma T = Surface tilt in tangential (x-y) plane
Gamma S = Surface tilt in sagittal (x-z) plane
ND = Refractive index in D light
NF = Refractive index in F light
NC = Refractive index in C light
Surface number

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UNIVAC 1108 – FORTRAN CODING SHEET

STATEMENT NO.	CONT.	FORTRAN STATEMENT	IDENTIFICATION STATEMENT

```
8141 GREG HEARN   EXAMPLE 1
   4 17   1    2  1     1   4  1  0.0       7.0        -3.5       3.5
   1  1   7000.       0.00
   1  2   -1.5        3.00
   1  3   -1.0        3.35
   1  4   7000.       5.801
   2  1   1.0         1.0         1.0       0.9        0.0
   2  2   1.51124     1.5169      1.50883   0.4        0.0
   2  3   1.0         1.0         1.0       0.9        0.0
   2  4   1.0         1.0         1.0       3.0        0.0
   5 17   50000       10.0        0.0       0.44       0.00001    3.350
   7  2   40.0        5.0
0.100     1.0               2     1      2
0.100     1.0               3     1      2
3.5  1.0  10.0  1.0   1.0   1.0   10.0  1.0   1.0  1.0   1.0  1.0  1.0  1.0
0.200     1.0               4     2      3
2.5  1.0  1.0   1.0   1.0   1.0   1.0   1.04  1.0  1.0   1.0  1.0  1.0  1.0
```

FIGURE 6. Sample Input Data Coding Sheet.

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The second grouping of columns on sheet 1 refers to

AY, AZ = Second-order aspheric terms (x-y and x-z planes, respectively)

B, C, D, E = 4th-, 6th-, 8th-, and 10th-order aspheric terms, respectively

H Max. = Maximum aperture at each surface (measured from the vertex to outer edge of the element)

H Min. = Minimum aperture at each surface (measured from the vertex to inner edge of the element)

The following information appearing on sheet 1 of Figure 7 is output from the design section. Refer to Table 2 for definitions of these terms.

BF = Indicates correction for back focus

EFL = Effective focal length

SA = Spherical aberration

ZSA = Zonal spherical aberration

PC = Primary curvature

CM = Coma

AT = Astigmatism

OST = Oblique spherical (tangential)

OSS = Oblique spherical (sagittal)

LCH = Longitudinal (transverse axial color)

TCH = Lateral color

ZSL = Lower zonal spherical

ZSU = Upper zonal spherical

The numbers directly under these columns are the values of these terms at each iteration. The numbers under each of these rows and indented somewhat are the values the program generated for these variables, the user specified as changeable.

In general, iterations will continue until the user specified limit is reached unless a solution for the problem is reached beforehand. Occasionally though, the terms chosen to be minimized can work in opposition--i.e., as one increases, the other reduces. This situation can cause an oscillation in the values of the aberration terms. When this happens it is quite possible that the best solution is not the last iteration results, instead an earlier iteration may display the optimum configuration.

In the last three rows of the design output one finds the final iteration term values in the first row and numbers which are related to the rates of change in these term values in row two. In row three are numbers that refer to the relative weighting of aberrations to be corrected.

Sheet 2 of the sample output (Figure 7) and subsequent sheets are the output of the ray-trace mode. The first two groupings of columns on sheet 2 contain the data that was input to the ray-trace section. In this example, the design section, which always automatically calls for a ray trace, uses data calculated in the last design iteration for input ray-trace data. (Note the change in R_2 and R_3 made by the design section.)

The next grouping of columns contain data for each ray at each surface. A diagram illustrating these terms and definitions of the terms is presented in Figure 8.

The unlabeled three-digit column of integers defines the ray number and surface number for each row. For example, 101 means the row contains data for the first ray and the first surface, 904 means the row contains data for the ninth ray and the fourth surface. The two remaining unlabeled columns represent back focus and effective focal length.

When the design section is used, the output ray data is printed for nine rays at each surface of the system. After the ray data is printed, three rows of data with eight columns in each row are printed. Row one consists of:

1. Range of object

2. Elevation of object in degrees below the horizontal (x-y plane)

3. Aximuth angle in degrees from the horizontal (x-z plane)

4. 5. and 6. The x, y, and z positions of the energy centroid at the image plane (meaningful only for individual ray traces not for design called ray traces)

7. Number of rays reaching last surface (check for vignetting and internal reflections)

8. Diameter of the root mean square spot size

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Row two and row three are related. Each column in row two represents a radius about the energy centroid; in row three, below each radius is a number which describes how many rays are contained within the annulus formed by the previous column's radius and the present column's radius. In the first column case the number of rays refer to the number within the circle defined by the first column's radius about the centroid. Rows two and three are not meaningful when the design section initiates a ray trace.

Below the three rows of data just explained is a second grouping of ray-trace data. This output data contains the results of the ray-trace mode when the second refractive index specified on the NS = 2 card is used. In other words, the data is information about rays traced through the system for a different color.

The three rows following this group of ray-trace data are the same as the first group of three rows, with the exception that the numbers of rays contained within the annuluses are cumulative for the two colors. The same is true for the three rows following the ray-trace data for the third-color rays.

R	XV	YV	ZV	GAMMA T	GAMMA S	N D	N F	N C	
7000.00000	.500000	.000000	.000000	.000000	.000000	1.000000	1.000000	1.000000	1
-1.53000	3.000000	.000000	.000000	.000000	.000000	1.511240	1.516900	1.508830	2
-1.00000	3.350000	.000000	.000000	.000000	.000000	1.000000	1.000000	1.000000	3
7000.00000	6.861000	.000000	.000000	.000000	.000000	1.000000	1.000000	1.000000	4

A Y	A Z	B	C	D	E	H MAX.	H MIN.	
.000000	.000000	.000000	.000000	.000000	.000000	.900000	.000000	1
.000000	.000000	.000000	.000000	.000000	.000000	.900000	.000000	2
.000000	.000000	.000000	.000000	.000000	.000000	.900000	.000000	3
.000000	.000000	.000000	.000000	.000000	.000000	3.000000	.000000	4

BF	EFL	SA	ZSA	PC	CM	AT	OST	OSS	LCH	TCH	ZSL	ZSU
.718344	4.5285	-1.268116	-.632224	-.297023	-.119965	-.164866	-1.535571	.000119	-.078302	-.014864	-.291044	-.926953
	-.32493+01	-.11315+01										
-.570605	3.0403	-.607438	-.298121	-.222766	-.020778	-.127918	-.719047	.000026	-.050317	-.008069	-.132261	-.436368
	-.45118+02	-.15717+01										
-.491989	3.0073	-.293797	-.144269	-.207840	.001321	-.116531	-.337950	.000003	-.049102	-.007943	-.056579	-.203619
	-.47186+02	-.16084+01										
.037384	3.4935	-.254173	-.125426	-.228466	-.001450	-.124706	-.295606	-.000058	-.057034	-.010114	-.044995	-.172244
	.45768+03	-.16623+01										
-.000194	3.4469	-.237523	-.117188	-.234105	.001441	-.131693	-.267301	-.000091	-.056342	-.009652	-.041120	-.160018
	-.27105+02	-.13908+01										
.125640	3.5674	-.261977	-.129352	-.241331	-.000983	-.135174	-.297085	.000144	-.058459	-.009918	-.046525	-.177694
	-.51516+02	-.16114+01										
.032230	3.4808	-.253017	-.124852	-.235226	-.000012	-.131623	-.267141	-.000026	-.056947	-.009301	-.044736	-.171405
	-.52684+02	-.18202+01										
.048463	3.4927	-.251547	-.124141	-.238873	.000486	-.134894	-.262541	-.000039	-.057189	-.009232	-.044315	-.170248
	-.28959+02	-.17912+01										
.086939	3.5324	-.262349	-.129501	-.238751	-.000885	-.133559	-.298071	.000104	-.057860	-.009556	-.046773	-.178125
	-.55969+02	-.18130+01										
.025742	3.4748	-.252152	-.124420	-.234436	.000078	-.131016	-.286514	.000034	-.056840	-.010102	-.044553	-.170788
	-.52333+02	-.18207+01										
.050849	3.4956	-.251560	-.124150	-.237420	.000343	-.133381	-.284136	.000122	-.057226	-.011029	-.044308	-.170248
	-.36070+02	-.15045+01										
.071968	3.5137	-.257467	-.127080	-.242298	.000244	-.137591	-.287693	-.000051	-.057594	-.009222	-.045652	-.174555
	-.28068+02	-.17834+01										
.076030	3.5242	-.263785	-.130299	-.236914	-.001196	-.131959	-.301353	.000079	-.057701	-.010196	-.047213	-.179385
	-.77484+02	-.16208+01										
.010466	3.4638	-.249046	-.122675	-.229526	-.000267	-.126566	-.286756	.000091	-.056583	-.009656	-.043864	-.168539
	-.15913+03	-.18504+01										
.030262	3.4815	-.242336	-.119585	-.230392	-.000040	-.127091	-.277630	-.000027	-.056845	-.008771	-.042160	-.163473
	-.19983+03	-.18611+01										
.044326	3.4944	-.240387	-.118636	-.231530	-.000029	-.127921	-.275829	-.000145	-.057051	-.010660	-.041630	-.161969
	-.22874+03	-.18549+01										
.044326	3.4944	-.240387	-.118636	-.231530	-.000029	-.127921	-.275829	-.000145	-.057051	-.010660	-.041630	-.161969
.928685	4.3083	-.194230	-.096302	-.278065	-.000699	-.153243	-.220532	.000128	-.070495	-.012177	-.026595	-.123847
.000000	.0000	.000000	.000000	.000000	.000000	.000000	.000000	.000000	.000000	.000000	.000594	

FIGURE 7. Sample Output Data (Sheet 1 of 4).

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R	XV	YV	ZV	GAMMA T	GAMMA S	N D	N F	N C	
7000.00000	.500000	.000000	.000000	.000000	.000000	1.000000	1.000000	1.000000	1
-228.74419	3.000000	.000000	.000000	.000000	.000000	1.511240	1.516900	1.508830	2
-1.86493	3.350000	.000000	.000000	.000000	.000000	1.000000	1.000000	1.000000	3
7000.00000	6.801000	.000000	.000000	.000000	.000000	1.000000	1.000000	1.000000	4

A Y	A Z	B	C	D	E	H MAX.	H MIN.	
.000000	.000000	.000000	.000000	.000000	.000000	.900000	.000000	1
.000000	.000000	.000000	.000000	.000000	.000000	.900000	.000000	2
.000000	.000000	.000000	.000000	.000000	.000000	.900000	.000000	3
.000000	.000000	.000000	.000000	.000000	.000000	3.000000	.000000	4

H	X	Y	Z	THETA T	THETA S			
.44000	.500014	.440000	.000000	.000503	.000000	101	************	************
.44002	2.999577	.440022	.000000	.037618	.000000	102	-667.187630	-670.153915
.44336	3.297299	.440217	.000000	-7.186766	.000000	103	6.788463	3.517072
.00158	6.801000	-.001561	.000000	-7.186766	.000000	104	6.788463	3.517072
.31113	.500007	.311127	.000000	.000356	.000000	201	************	************
.31114	2.999789	.311143	.000000	.026600	.000000	202	-667.187866	-670.154289
.31239	3.323836	.311293	.000000	-4.961299	.000000	203	6.909827	3.597558
.00945	6.801000	.009447	.000000	-4.961299	.000000	204	6.909827	3.597558
.00001	.500000	.000010	.000000	.000000	.000000	301	************	************
.00001	3.000000	.000010	.000000	.000001	.000000	302	-667.188148	-670.154694
.00031	3.350009	.000010	.000000	-.000156	.000000	303	7.028092	3.675989
.00000	6.801000	.000001	.000000	-.000156	.000000	304	7.028092	3.675989
.06253	.500000	-.062532	.000000	9.999930	.000000	401	.854639	.360109
.37823	2.999687	.378227	.000000	6.630652	.000000	402	-.253989	.541549
.41615	3.303569	.413552	.000000	3.446978	.000000	403	-3.562215	1.040034
.62422	6.801000	.624216	.000000	3.446978	.000000	404	-3.562215	1.040034
.50252	.500018	-.502522	.000000	9.999434	.000000	501	3.350126	2.894070
.06173	2.999992	-.061734	.000000	6.592422	.000000	502	3.534166	4.377149
.02130	3.349379	-.021298	.000000	10.335348	.000000	503	3.466665	2.800982
.60808	6.801000	.606077	.000000	10.335348	.000000	504	3.466665	2.800982
.50254	.500018	-.502542	.000000	9.999434	.000000	601	3.350239	2.894186
.06175	2.999992	-.061754	.000000	6.592420	.000000	602	3.534339	4.377324
.02132	3.349878	-.021318	.000000	10.335670	.000000	603	3.466771	2.801007
.60808	6.801000	.606077	.000000	10.335670	.000000	604	3.466771	2.801007
.94253	.500063	-.942532	.000000	9.998938	.000000	701	5.846007	5.428395
.50137	2.999450	-.501870	.000000	6.554164	.000000	702	7.367592	8.257507
.47227	3.290203	-.468465	.000000	18.415078	.000000	703	4.697224	2.983652
.70045	6.801000	.700448	.000000	18.415078	.000000	704	4.697224	2.983652
.66794	.500032	-.502532	.440000	9.999434	.000511	801	.854670	.360109
.44434	2.999569	-.061821	.440022	6.592414	.038250	802	-.254124	.541548
.44424	3.297090	-.027437	.440221	10.455062	-7.406456	803	-4.066964	1.143951
.62476	6.801000	.624575	-.015353	10.455063	-7.406456	804	-4.066964	1.143951
.50253	.500018	-.502532	.000010	9.999434	.000000	901	3.350125	2.894070
.06176	2.999992	-.061744	.000010	6.592421	.000001	902	3.534166	4.377149
.02131	3.349878	-.021368	.000010	10.335509	-.000160	903	3.466665	2.800982
.60808	6.801000	.606077	.000000	10.335509	-.000160	904	3.466665	2.800982

.5000000+05	.1000000+02	.0000000	.6801000+01	.4201484+00	-.1709230-02	.9000000+01	.5930031+00
.4000000+02	.8000000+02	.1200000+03	.1600000+03	.2000000+03	.2400000+03	.2800000+03	.3200000+03
.9000000+01	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000

.44000	.500014	.440000	.000000	.000503	.000000	101	************	************
.44002	2.999577	.440022	.000000	.037889	.000000	102	-662.396194	-665.362724
.44336	3.297298	.440219	.000000	-7.268073	.000000	103	6.749003	3.477934
.00663	6.801000	-.006631	.000000	-7.268073	.000000	104	6.749003	3.477934

FIGURE 7. Sample Output Data (Sheet 2 of 4).

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.31113	.500007	.311127	.000000	.000356	.000000	201	************	************
.31116	2.999769	.311143	.000000	.026792	.000000	202	-662.396439	-665.363098
.31239	3.323836	.311294	.000000	-5.016805	.000000	203	6.869964	3.557855
.00605	6.801000	.006054	.000000	-5.016805	.000000	204	6.869964	3.557855
.00001	.500000	.000010	.000000	.000000	.000000	301	************	************
.00001	3.000000	.000010	.000000	.000001	.000000	302	-662.396713	-665.363495
.00001	3.350000	.000010	.000000	-.000158	.000000	303	6.987815	3.635721
.00000	6.801000	.000001	.000000	-.000158	.000000	304	6.987815	3.635721
.06253	.500000	-.062532	.000000	9.999930	.000000	401	.654639	.360109
.37823	2.999667	.378227	.000000	6.606158	.000000	402	-.266169	.543548
.41602	3.303598	.413424	.000000	3.376281	.000000	403	-3.704120	1.061786
.61976	6.801000	.619755	.000000	3.376281	.000000	404	-3.704119	1.061786
.50252	.500018	-.502522	.000000	9.999434	.000000	501	3.350126	2.694070
.06173	2.999992	-.061734	.000000	6.567657	.000000	502	3.536198	4.393581
.02145	3.349877	-.021452	.000000	10.341569	.000000	503	3.467432	2.799316
.60831	6.801000	.608311	.000000	10.341569	.000000	504	3.467432	2.799316
.50254	.500019	-.502542	.000000	9.999434	.000000	601	3.350239	2.694186
.06175	2.999992	-.061754	.000000	6.567655	.000000	602	3.536372	4.393757
.02147	3.349876	-.021472	.000000	10.341894	.000000	603	3.467538	2.799340
.60831	6.801000	.608311	.000000	10.341894	.000000	604	3.467538	2.799340
.94253	.500063	-.942532	.000000	9.999978	.000000	701	5.846007	5.428395
.50187	2.999450	-.501870	.000000	6.529126	.000000	702	7.384490	8.289034
.47240	3.290168	-.463597	.000000	18.514958	.000000	703	4.689444	2.968116
.70713	6.801000	.707130	.000000	18.514958	.000000	704	4.689444	2.968116
.66796	.500032	-.502532	.440000	9.999434	.000511	801	.654670	.360109
.44434	2.999569	-.061821	.440022	6.567649	.038523	802	-.266296	.543547
.44425	3.297068	-.027563	.440222	10.462419	-7.492357	803	-4.242180	1.171788
.62536	6.801000	.625039	-.020601	10.462419	-7.492357	804	-4.242180	1.171788
.50253	.500018	-.502532	.000010	9.999434	.000000	901	3.350126	2.694070
.06174	2.999992	-.061744	.000010	6.567656	.000001	902	3.536195	4.393581
.02146	3.349876	-.021462	.000010	10.341732	-.000162	903	3.467432	2.799315
.60831	6.801000	.608311	.000000	10.341732	-.000162	904	3.467432	2.799315
.5000000+05	.1000000+02	.0000000	.6801000+01	.4198675+00	-.1999100-02	.1800000+02	.5948168+00	
.4000000+02	.8000000+02	.1200000+03	.1600000+03	.2000000+03	.2400000+03	.2800000+03	.3200000+03	
.1800000+02	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	
.44000	.500014	.440000	.000000	.000503	.000000	101	************	************
.44002	2.999577	.440022	.000000	.037502	.000000	102	-669.259872	-672.226059
.44336	3.297299	.443217	.000000	-7.152158	.000000	103	6.805529	3.534001
.00057	6.801000	.000568	.000000	-7.152158	.000000	104	6.805529	3.534001
.31113	.500007	.311127	.000000	.000356	.000000	201	************	************
.31116	2.999789	.311143	.000000	.026519	.000000	202	-669.260117	-672.226433
.31239	3.323836	.311292	.000000	-4.937669	.000000	203	6.927068	3.614731
.01089	6.801000	.010891	.000000	-4.937669	.000000	204	6.977068	3.614731
.00001	.500000	.000010	.000000	.000000	.000000	301	************	************
.00001	3.000000	.000010	.000000	.000001	.000000	302	-669.260399	-672.226845
.00001	3.350000	.000010	.000000	-.000155	.000000	303	7.045515	3.693407
.00000	6.801000	.000001	.000000	-.000155	.000000	304	7.045515	3.693407
.06253	.500000	-.062532	.000000	9.999930	.000000	401	.654639	.360109
.37823	2.999667	.378227	.000000	6.641137	.000000	402	-.246806	.540695
.41621	3.303556	.413607	.000000	3.477087	.000000	403	-3.503535	1.031040
.62612	6.801000	.626116	.000000	3.477087	.000000	404	-3.503534	1.031040
.50252	.500018	-.502522	.000000	9.999434	.000000	501	3.350126	2.694070
.06173	2.999992	-.061734	.000000	6.603024	.000000	502	3.533301	4.370152
.02123	3.349879	-.021232	.000000	10.332710	.000000	503	3.466336	2.601689

FIGURE 7. Sample Output Data (Sheet 3 of 4).

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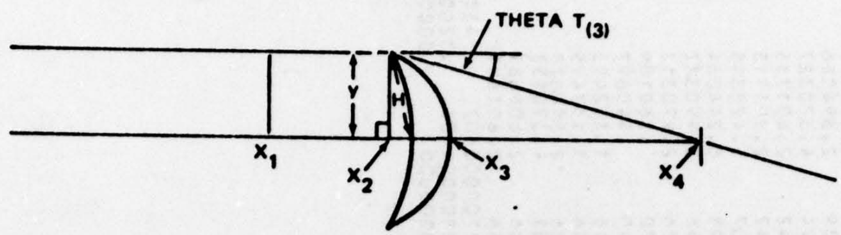
.60798	6.801000	.607978	.000000	10.332710	.000000	504	3.466336	2.801689
.50254	.500015	-.502542	.000000	9.999434	.000000	601	3.350239	2.894186
.06175	2.999992	-.061756	.000000	6.603022	.000000	602	3.533474	4.370327
.02125	3.349879	-.021252	.000000	10.333031	.000000	603	3.466442	2.801715
.60798	6.801000	.607978	.000000	10.333031	.000000	604	3.466442	2.801715
.94253	.500063	-.942532	.000000	9.998938	.000000	701	5.646007	5.428395
.50127	2.999450	-.501879	.000000	6.564682	.000000	702	7.360398	8.244084
.47221	3.290218	-.462405	.000000	16.372595	.000000	703	4.700556	2.990312
.69751	6.801000	.697609	.000000	18.372595	.000000	704	4.700556	2.990312
.66794	.500032	-.502532	.440000	9.999434	.000511	801	.654670	.360109
.44634	2.999569	-.041821	.440022	6.603016	.036134	802	-.248940	.540697
.44623	3.297091	-.027391	.440220	10.451941	-7.372747	803	-3.994856	1.132495
.62452	6.801000	.624379	-.013163	10.451941	-7.372747	804	-3.994856	1.132495
.50253	.500018	-.502532	.000010	9.999434	.000000	901	3.350126	2.894878
.06174	2.999992	-.061744	.000010	6.603023	.000001	902	[illegible]	4.370152
.02124	3.349679	-.021242	.000010	10.332870	-.000160	903	3.466336	2.801689
.60798	6.801000	.607978	.000000	10.332870	-.000160	904	3.466336	2.801689

.5009000+05	.1000000+02	.0000000	.6800999+01	.4200412+00	-.1820251-02	.2700000+02	.5937058+00
.4000000+02	.2000000+02	.1200000+03	.1600000+03	.2000000+03	.2400000+03	.2800000+03	.3200000+03
.2700000+02	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000	.0000000

FIGURE 7. Sample Output Data (Sheet 4 of 4).



H - DISTANCE OF RAY'S INTERSECTION WITH SURFACE FROM VERTEX.
X - POSITION ALONG X-AXIS OF A PERPENDICULAR DROPPED FROM THE INTERSECTION OF THE SURFACE AND THE RAY.
Y - RAY HEIGHT MEASURED ALONG THE ABOVE-DESCRIBED PERPENDICULAR IN Y-PLANE.
Z - RAY HEIGHT MEASURED ALONG THE ABOVE-DESCRIBED PERPENDICULAR IN Z-PLANE.
THETA T - RAY ANGLE AFTER INTERSECTION WITH THE SURFACE, MEASURED IN DEGREES OFF THE HORIZONTAL IN TANGENTIAL PLANE.
THETA S - SAME AS THETA T, BUT IN SAGITTAL PLANE.

FIGURE 8. Illustration of Ray-Data Terms.

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TROUBLESHOOTING

Occasionally attempts to solve new problems will result in error messages whose meanings are not immediately obvious. The following list of errors and corrections is presented to give a few starting points in problem debugging. At the end of the list is included one problem that does not produce an error message.

Error: *"No plotter initialization routine has been called..."*

Check: N1 = 6 or N1 = 7 cards. Make sure either one or the other is present and that N1 is contained in column 4.

Error: *"Ray height exceeds maximum aperture at interface No. ..."*

Check: Y values versus H values at each X location for the ray in question as follows:

1. If Y and H values are nearly equal and the X value is near the specified surface location, a simple re-evaluation of the surface aperture size (N1 = 2 card), field angle, entrance pupil diameter, or limiting aperture location (all specified on either the N1 = 4 or 5 card) may be required.

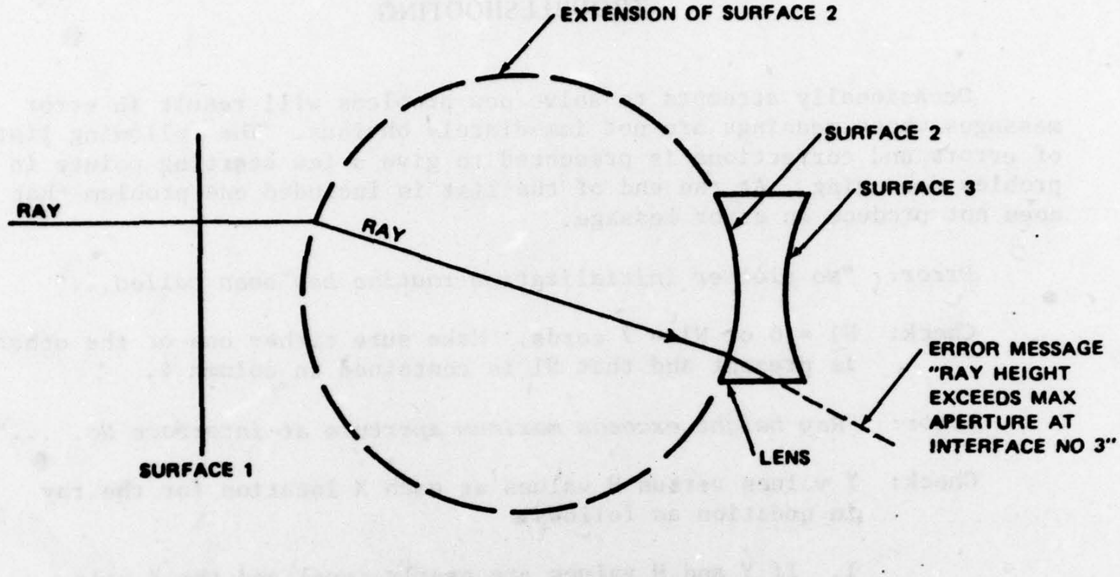
2. If Y and H values differ significantly and if the X value deviates from the specified interface location, check the following:

   a. The surface cards and numbering to see that they are ordered in the sequence that the rays are expected to reach the surfaces. Watch out for negative lens thicknesses as a result of design mode changes.

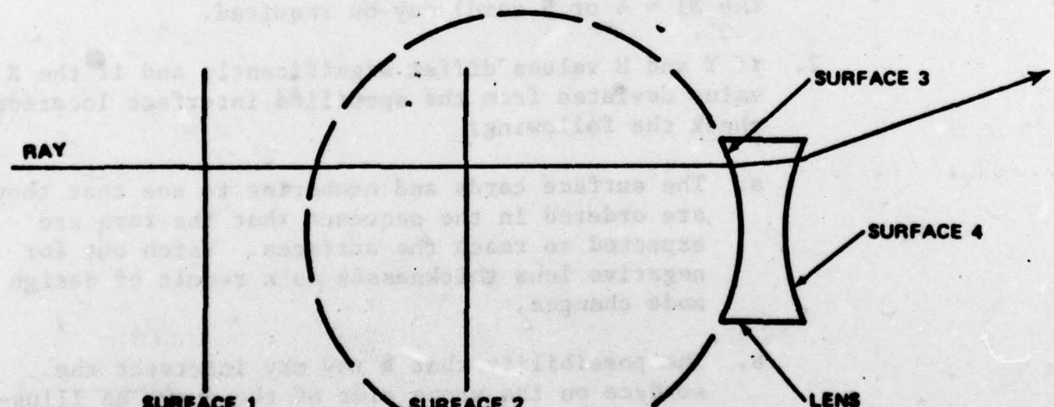
   b. The possibility that a ray may intersect the surface on the wrong side of the curve as illustrated in Figure 9(a) and (b). To prevent this, insert a dummy plane surface immediately before the surface exhibiting this difficulty.

Error: *"** Points out of Range **"*

Check: Graphics scale limits specified on the card preceding N1 = 1 cards. Points can be out of range in either the X or Y direction. Also check which surface was specified for the starting point of the graphics output.



(a) ERRONEOUSLY REFRACTED RAY



(b) SITUATION CORRECTED BY INTRODUCING DUMMY SURFACE NO. 2

FIGURE 9. Illustrations of Ray Intersection.

Error: *"Ray internally reflected at interface ..."*

Check: For tight curvatures and high indexes of refraction. Adjust shapes or focal lengths to accommodate rays.

Error: *"The interpretation of meaningless data was attempted."*

Check: Card formats, card sequencing, characters punched on cards.

Error: *"Ray does not intersect interface number ..."*

Check: Position of sequential elements along optic axis. Rays will not reverse directions unless a mirror reflects them. Curvature too tight.

Problem: *Terms to be minimized are not improving or are not improving fast enough.*

Check:
1. Formatting on aberration minimization specification card.
2. Adequate number of variables (one for each aberration to be minimized and always ≥ 2).
3. Large enough increment limits for each variable.
4. Number of possible iterations.
5. Variables selected are consistent with aberrations to be minimized. For instance to correct effective focal length one would not choose to change lens shape while retaining the same power.